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Mediterranean land systems: representing diversity and intensity of complex land systems in a dynamic region

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Abstract

In the Mediterranean region, land systems have been shaped gradually through centuries. They provide services to a large and growing population in a region that is among the most vulnerable to future global change. The spatial extent and distribution of Mediterranean land systems is, however, unknown. In this paper, we present a new, expert-based classification of Mediterranean land systems, representing landscapes as integrated social-ecological systems. We combined data on land cover, management intensity and livestock available on the European and global scale in a geographic information system based approach. We put special emphasis on agro-silvo-pastoral mosaic systems: multifunctional Mediterranean landscapes hosting different human activities that are not represented in common land cover maps. By analyzing location conditions of the identified land systems, we demonstrated the significance of both bio-physical (precipitation, soil) and socio-economic (population density, market influence) factors driving the occurrence of these systems. Agro-silvo-pastoral mosaic systems were estimated to cover 23.3% of the Mediterranean ecoregion and exhibited to a certain extent similar characteristics as forest and cropland systems. A reanalysis using data that are available with global coverage indicated that the choice of datasets leads to significant uncertainties in the extent and spatial pattern of these systems. The resulting land systems typology can be used to prioritize and protect landscapes of high cultural and environmental significance.

1. Introduction

In light of recent socio-economic developments and anticipated climate change impacts in the Mediterranean region, there is an urgent need for investigating the capacity of the region to sustain a variety of ecosystem services for a growing population. On one side, the European part of the region is home to high-input intensive agricultural systems significant for regional food production. On the other, the Middle Eastern and North African part is among the regions with the highest population growth, and dependency on food imports - with over half of the population relying on food produced elsewhere (Wright & Cafiero, 2011). The region is extremely vulnerable to fluctuations in food supply and prices, and expected climate change coupled with demographic growth could contribute to further regional instability and conflicts (Evans, 2008; Sowers *et al.*, 2010). Potential shocks to the society and economy have also been observed in the European part. The Greek financial crisis reportedly influenced the supply of agricultural products (Pfeiffer & Koutantou, 2015), impacting on land-use and environment.

In order to target policies to prioritize areas for agriculture, landscape conservation and biodiversity protection in the Mediterranean region, the characteristics and distribution of land systems need to be identified (Agnoletti, 2014). This is particularly valid for agro-silvo-pastoral mosaic systems where human influence and ecological conditions are intricately linked. Characteristics of such traditional landscapes are disregarded if represented by a single, dominant land cover type as is common in most current datasets (Turner *et al.*, 2007; Verburg *et al.*, 2011a). Moreover, when analyzing changes to these systems, land-use intensity is an important component besides changes in land cover, and has a significant environmental impact (Ellis & Ramankutty, 2008). Existing land cover and land systems mapping approaches are misrepresenting the extent or diversity of agro-silvo-pastoral mosaics (Zomer *et al.*, 2009) and often fail to integrate differences in land-use intensity. Although global and continental attempts to map land systems in the Mediterranean region were made, they focused on generalized cropland and grazing systems (van Asselen & Verburg, 2012; Dixon *et al.*, 2001; FAO, 2011), ignoring the specific mosaics unique to this region.

As a result of its environmental conditions, extremely long land-use history, and cultural diversity, the Mediterranean region is characterized by a wide variety of land systems that are not easily mapped. A good example is the dehesa/montado system, present in Spain and Portugal, which is highly valuable in the cultural heritage context (Meeus, 1995). In this system different activities, such as gathering of forest products, livestock grazing and cereal cultivation occur simultaneously (Joffre *et al.*, 1999). Using remote sensing imagery, we can receive information on the tree density of these systems, but not on the extent of grazing or crop cultivation below the trees (Plieninger & Schaar, 2008). Attempts to map these multifunctional systems have been made. In the European CORINE land cover data, they are represented as "Agroforestry areas", however substantial areas are also defined as other classes (Bunce *et al.*, 2008; EEA, 2015a).

In the Mediterranean region, landscapes are subject to two contrasting processes of change: abandonment of rural, mountainous and less developed areas on one side, and intensification and increasing human influence on the other (García-Llorente *et al.*, 2012; Nieto-Romero *et al.*, 2014). Soil degradation and water shortages are the main environmental problems in the region, as a consequence of land management and complex biophysical and climatic conditions (Almagro *et al.*, 2013; Guerra *et al.*, 2015). Furthermore, projected climate and socio-economic changes suggest that Mediterranean ecosystems are amongst the most vulnerable to future global change (Schröter *et al.*, 2005). Traditional agro-silvo-pastoral mosaic systems are particularly under pressure, threatening the provision of numerous ecosystem services and biodiversity in general (Zamora *et al.*, 2007). A significant number of plant and animals species, a lot of them endemic, are related to extensive management practices and these traditional landscapes. This is why the Mediterranean region was identified as one of the Global Biodiversity Hotspots (Cuttelod *et al.*, 2009).

In this paper we develop a spatial representation of Mediterranean land systems by integrating information on land management as an inseparable part of these landscapes. By investigating the location factors behind these land systems, we identify how different socio-economic and biophysical factors determine their distribution. At the same time, this study addresses the challenges of data and knowledge differences between different parts of the Mediterranean region. Finally, we evaluate the performance of our classification, by comparing it to existing studies in the region, and by analyzing the uncertainty related to available data.

2. Materials and methods

2.1 Study area

We defined the spatial extent of the Mediterranean region by focusing on areas surrounding the Mediterranean Sea that share similar climatic and other biophysical characteristics. We chose the spatial extent of the Mediterranean ecoregion (Fig. 1), as it describes the approximate extent of representative Mediterranean natural communities (Olson *et al.*, 2001). We included the Nile Delta and similar ecoregions within the Mediterranean ecoregion, such as the Apennine deciduous montane forests in central Italy. The total study area covers 2.3 million km^2 in 27 countries. Around 400 million people live within the ecoregion boundaries, and yearly 250 million tourists visit the area (31% of all international tourists), making it among the regions with highest human influence (Cuttelod *et al.*, 2009). The region is characterized by the

Mediterranean climate with dry summers and mild winters, when most precipitation takes place. The southern part of the region is predominantly arid and semi-arid, whereas the northern part is semi-arid to dry humid (Zomer *et al.*, 2008). Although the mean annual precipitation of the whole area is around 500 mm, a quarter of the area has below 300 mm of rainfall. This limits rainfed agriculture, particularly in the Middle East and North Africa part of the region.

2.2 Classification overview

We classified combinations of land cover, livestock density, irrigation extent and different intensity proxies (Table 1) using a Geographic Information System (GIS) based approach. By combining land cover with data on land management, we considered the anthropogenic aspects of Mediterranean land systems. This is necessary, as the management of a specific location depends on local combinations of socio-economic and biophysical conditions (Lambin *et al.*, 2001). Mediterranean land system classes were defined a-priori based on the common types distinguished in the literature.

We operated on a 2 km spatial resolution. Although a 2 km spatial resolution is arbitrary this would hold for any chosen resolution that aims to capture human-environment interactions. The choice of spatial resolution was based on: 1). The continental extent of the Mediterranean region and the spatial detail of available data. Although some of the data were available on a very high resolution (e.g. 25 m tree cover), most of it was available on a 1 km resolution (Table 1); 2). Land systems were defined by the set of activities at the farm or landscape level and not at the level of individual landscape components (Verburg et al., 2002), given the relatively small scale and high spatial variation within landscapes a 2 km spatial resolution was judged to be optimal for capturing variation in land systems; and 3). We aimed to represent global patterns of

Mediterranean land systems on a resolution able to capture the spatial variability of human-environment interactions in heterogeneous landscape mosaics (van Delden *et al.*, 2011; Pickett & Cadenasso, 1995).

2.3 Data

More data and data with higher thematic and spatial resolution were available for the European part of the region (Fig. 1). In contrast to studies that only use data that are consistently available across an entire study area, we used the best data available for different parts of the region. However, we restricted ourselves to data that covered multiple countries. National data were used to train the classification (e.g. by looking at the dehesa/montado extent). The following criteria were used when choosing the data: 1). Highest spatial resolution; 2). Data were as recent as possible; 3). Data underwent validation; 4). The data were not generated by downscaling based on population density. This way we could ensure independence of the data and later analyze how the occurrence of land systems relates to population distributions. All input maps were resampled to a resolution of 2 x 2 km in an Lambert equal area projection.

For land cover variables, we used tree cover (Hansen *et al.*, 2013), soil sealing data for Europe (EEA, 2015b), built up areas extent for the remaining part of the region (Jun *et al.*, 2014), cropland extent (Fritz *et al.*, 2015) and the extent of bare areas (Latham *et al.*, 2014). For identifying the extent of areas with permanent crops, we used the CAPRI-dynaspat data for the European Union part of the region (Britz & Witzke, 2014), the CORINE land cover permanent crops extent for the rest of Europe and Turkey (EEA, 2015a), and the SPAM data for the MENA region (You *et al.*, 2014).

Livestock distribution was obtained from the Gridded Livestock of the World v2.0 (Robinson *et al.*, 2014). We combined the numbers of bovines, goats and sheep. Livestock distribution was used to identify rangelands and grazing mosaic systems, and to define the intensity of grazing based on an existing grazing systems classification (Dixon *et al.*, 2001; FAO, 2011). We did not consider the distribution of pigs. Pigs are being grazed on a large extent in the dehesas/montados of the Iberian peninsula, where they are associated with traditional products such as the "jamón". Pigs in other parts of the Mediterranean are mostly attributed to landless livestock management patterns. Based on the data these two different systems could not be distinguished.

Irrigation plays a significant role in the Mediterranean region, where agriculture is constrained by water availability (Almeida *et al.*, 2013). Although irrigation cannot be related to agricultural intensity, irrigated systems have specific demands regarding water and energy (Fader *et al.*, 2016). To map irrigated systems, we used the data on areas equipped for irrigation from the Global Map of Irrigation Areas (Siebert *et al.*, 2005, 2013).

We used different indicators and proxies to characterize the intensity of land management, as data on this spatial scale is scarce. We used the European agricultural intensity map to identify areas with intensive rainfed cropland for the European Union part of the Mediterranean region (Temme & Verburg, 2011). For the remaining area, we used the global field size map, where we defined the areas with the largest field size class as intensive (Fritz *et al.*, 2015). While it is not possible to directly translate field size to intensity, field sizes can indicate the degree of investment, mechanization and labor intensity of agriculture (Kuemmerle *et al.*, 2013; Rodríguez & Wiegand, 2009). In addition, areas within the 10th percentile of crop yields in the non-EU Mediterranean region were identified as intensive. We focused on the most significant crops in the Mediterranean region: wheat and other cereals, together with vegetables for annual crops;

and tropical and temperate fruits (among them grapes), together with olives for permanent crops (Daccache *et al.*, 2014).

For forest management intensity, we used the European forest management map with defined areas of high forest harvesting intensity (Hengeveld et al., 2012). We identified planted forests by looking at areas with a high share of plantation species using the European tree species map (Brus et al., 2012; Verkerk et al., 2015). For the non-European part of the Mediterranean region, no such data is available. Therefore we used the forest losses and gains data between 2000 and 2014 to identify areas with high intensity of forest management, defined by the cycles of felling and replanting. If the landscape, defined by the 2 km spatial resolution, experienced both high losses and high gains in the observed time, we assumed it being a high intensity forest. If a significant increase of forests occurred in the observed time, we defined it as a planted forest. We assumed it is unlikely, that in a semi-arid environment vast areas would be reforested naturally in such a short time.

2.4 Expert-based classification

We used an expert-based hierarchical classification procedure (Fig. 2, Supplement A). Classification rules were defined as conditional thresholds based on literature on Mediterranean farming, grazing, agro-silvo-pastoral and forest systems (full list of literature considered in Supplement B). This way, our classification followed common understanding of the characteristics of Mediterranean land systems. Expert-based hierarchical classification procedures have been used to identify land and farming systems in numerous cases (Dixon *et al.*, 2001; van de Steeg *et al.*, 2010). We follow a similar classification procedure as van Asselen and Verburg (2012) and the LADA project (FAO, 2011). However, none of these approaches dealt with complex mosaic systems specific for the Mediterranean. Compared to statistical clustering classification (Ellis & Ramankutty, 2008; Letourneau *et al.*, 2012; Václavík *et al.*, 2013), expert based classification is less sensitive to the selected distance metric and criteria for determining the order of clustering (van Asselen & Verburg, 2012). A detailed comparison between expert-based and statistically derived typologies for landscapes is provided by van der Zanden et al. (2016). Our hierarchy was based on management intensity. Land systems were identified using different intensity indicators, and systems with low intensities were defined as areas where these indicators do not show a high intensity. More intensive systems overwrote less intensive ones, when more than one system fulfilled the classification criteria.

First, we defined settlement systems as areas with a high percentage of built-up areas. On a 9 cell neighborhood we performed focal statistics and subsequently applied a majority filter to the European sealed soil and the global land cover 30 maps. By looking at the immediate neighboring cells as well, we identified larger built-up landscapes and removed individual cells with high shares of built-up areas. Other systems that were defined by the dominant land cover were systems occurring on bare (desert) areas, and wetlands (Supplement A). If later in the classification stage we identified a high intensity cropland system at the same location as a wetland, it was overwritten. For example, the Guadalquivir river estuary is defined as a wetland, however a large portion of it is cultivated. This way, we resolved inconsistencies between data sets and differences in definition (the high intensity cropping system is still in a wetland area). After this step we continued with the classification of cropland, forest, grazing systems and agro-silvo-pastoral mosaics.

Cropland, Forest, grazing and agro-silvo-pastoral mosaic land systems were at first defined by the cropland extent and tree cover. Cropland systems were associated with high cropland extent and were further subdivided depending on their intensity, presence of irrigation and combinations of crop type. Forest systems occur on areas with a high tree density, and were subdivided based on their protection status and harvesting intensity. Grazing systems were subdivided based on whether they occur in semiarid or arid areas or grasslands, and their livestock density.

The remaining agro-silvo-pastoral mosaic systems represent multifunctional agroforestry landscapes. We identified them by looking at the activities they host: cropland, livestock grazing, woodlands. We classified them based on their tree cover (open or closed woodlands), cropland extent, and livestock density.

2.5 Analysis of location factors

The observed distribution of land systems reflects the continuity of land management as a response to socio-economic and biophysical conditions (Fuchs et al., 2013). We performed binominal logistic regressions to investigate the role of these conditions. This way we could calculate the probability of each location to host a specific land system, an approach often used to explain existing land-use patterns (Letourneau *et al.*, 2012). Logistic regressions were performed for all land systems separately using 20 variables (Table 2).

Biophysical variables describe the suitability for growing crops, encouraging or constraining agricultural activities (Panagos *et al.*, 2013). We selected seven soil characteristics: sand, clay and organic content, cation exchange capacity (CEC), pH, drainage and soil depth. We used the soil characteristics valid for natural vegetation conditions to omit potential correlation between e.g. forest cover and organic content (Stoorvogel *et al.*, 2016). We also tested the soil characteristics of the current land cover situation. Temperature, precipitation, solar radiation and potential evapotranspiration are climatic variables that limit growth of vegetation. Although aridity limits the growth of vegetation, we had to omit the CGIAR aridity index map to avoid multicollinearity (Zomer *et al.*, 2008) as it was highly correlated to precipitation (Pearson correlation >0.9). Lastly, we studied how potential natural vegetation explains the natural vegetation characteristics of land systems.

Socio-economic factors were represented by five variables. Population density and density of rural population characterize the type of activities expected in an area, and the degree of human impact (Neumann *et al.*, 2015). The market influence index specifies the capital available to agricultural production, investing in its expansion or intensification (Verburg *et al.*, 2011b). Accessibility to national and international markets is an indicator for the potential to market goods provided by the land systems (Verburg *et al.*, 2011b). Finally, we investigated the role of road infrastructure, by including the distance to roads.

The regression was performed on a balanced sample of 5% of all grid cells for each land system (with a minimum sample of 1000 points - 500 for presence and 500 for absence). To reduce spatial autocorrelation while retaining a sufficiently large sample size, we applied a minimum distance of one cell (4 km) between the sample points. We performed a forward conditional regression. We used the ROC (Receiver Operating Characteristic) as a measure for the goodness of fit of our regression model. Multiple samples were taken to ensure robustness of the identified relations. Only for very small land systems (e.g. planted forests) this was not possible. For none of the land systems we found major differences between the results based on different samples.

2.6 Classification performance and data uncertainty

Assessing the performance of a land systems classification is a difficult task, and cannot be performed using traditional approaches applied in remote sensing or spatial simulation. Any classification system is as good as its potential use and the quality of the underlying data. For example, validation using high resolution satellite images or land cover products could only be used to identify the category of land system (forest, cropland systems), without validating the intensity. For being a useful classification, identified land systems should correspond to common descriptions of these systems and be related to land systems found in field studies. We performed a documented expert based validation, where we gathered studies from the whole Mediterranean region. We collected 190 studies on land management from peer reviewed papers, book chapters and conference proceedings (Supplement B). The studies were selected based on the following criteria: 1). The study clearly defined a land system characteristic, such as intensity or the mosaic nature of the system (e.g. intensive tomato production, dehesa); 2). The study was associated to a specific location (Mediterranean or nationwide studies were omitted); 3). It was based on an actual system and not on experiment sites. We registered the locations of all studies, together with the information of their land system characteristics (type, intensity, management). The accuracy of the final land systems map was then assessed by comparing how well it represents the documented land systems. Studies on urban areas (Mediterranean cities) were omitted, as they completely correspond with the locations of cities and would falsely contribute to a higher accuracy.

To analyze the uncertainty related to the differential quality of data, we applied the same classification criteria using the data with the lowest quality but global coverage (Table 1). High resolution data covering the European part of the region were thus not used. The two maps were compared in terms of agreement or disagreement of quantity and location (Pontius & Santacruz, 2014).

3. Results

3.1 Land systems

The distribution of Mediterranean land systems is shown in Figs. 3, 4 and 5. Average values for land systems in terms of bare, tree and cropland cover, and livestock density are presented in Fig. 6 and Supplement C.

3.1.1 Bare and open grazing systems

Bare and open grazing systems cover 22.6% of the Mediterranean region, mostly in North Africa and the Middle East. They are divided into grazing systems in arid environments and grazing systems in open rangelands. Arid systems are further subdivided into bare areas and deserts without notable livestock presence, and extensive and intensive arid grazing. In some parts (e.g. Syria), livestock density in deserts can reach over a 1000 heads of combined sheep, goats and bovines per km^2. Open rangelands are subdivided into extensive and intensive, and occur primarily in open landscapes of the Iberian peninsula, North Africa, Turkey and the Western Balkans. They occur in areas without bare cover and have a relatively high percentage of cropland (over 20%).

3.1.2 Cropland systems

Cropland systems cover 37.8% of the region, significantly higher than the estimated global average of 8% (van Asselen & Verburg, 2012). This makes them the most represented land system group in the Mediterranean region. They are defined by a high average of cropland cover of over 45% but also contain significant portions of tree and bare cover. Cropland systems are divided into three categories: extensive, intensive rainfed and irrigated, and are further subdivided into annual and permanent crop systems, and mosaics of annual and permanent crops. Extensive systems cover vast areas in North Africa, the Middle East and the Anatolian plateau in Turkey. Intensive rainfed cropland systems mostly occur in the Northern Mediterranean (Spain, Italy, France, parts of Turkey) with the notable exception of northern Tunisia. Irrigated systems occur throughout the region, often along major rivers (Nile in Egypt, Euphrates and Tigris in Turkey and Syria, Guadalquivir in Spain, Sebou and Sous in Morocco.

3.1.3 Forest systems

The global estimate for forest systems is 21% of the global surface (van Asselen & Verburg, 2012), whereas in the Mediterranean region we estimate these systems to cover 10.1%. Forest systems are characterized by a high, over 40% average tree cover. Notable portions of areas with higher tree density are however represented as agro-silvo-pastoral mosaic systems (e.g. closed wooded rangelands). Forest systems together with such dense tree cover mosaic systems cover 25.2% of the Mediterranean region. More than half of all forest areas are thus used for cultivation and grazing. Most of the forests are in the mountainous regions of the European Mediterranean. In the MENA region, continuous forest systems are situated in the Atlas mountains spanning from Morocco to Tunisia (Fig. 5). Extensive areas covered by Mediterranean forest systems occur on Corsica, the most forested Mediterranean island (Fig. 4b). Most of the forests are defined by medium intensity management (61.1%), followed by natural and semi-natural forests (25.5%). A lower extent of forests is characterized by high intensity management (10%) or as planted forests (3.4%), mostly occurring on the Iberian peninsula.

3.1.4 Agro-silvo-pastoral mosaics

Mosaic systems cover 23.3% of the Mediterranean - this is substantially higher compared to the 4–9% global estimates of mosaic cropland, grassland and forest systems (van Asselen & Verburg, 2012). They are characterized by a medium to high average cropland cover (14 to 60%), and hold a considerable portion of areas covered by tree cover. The four woodland/wooded rangeland classes, would be represented as forest cover in an approach focusing on dominant land cover. In this study, they however represent landscapes, where forest activities coincide with grazing and arable cultivation. The open woodland class represents areas with moderate average tree cover (17.2%) and a lower livestock density (31.2 animals/km^2). Open wooded rangelands have a similar average tree cover (16.0%), however a higher average livestock density (84.5 animals/km^2). The cropland and wooded rangeland mosaic systems are also defined by a high average cropland cover of 39.0%. All three open woodland systems occur in the whole Mediterranean region, with the most notable examples of the dehesa/montado system of the Iberian peninsula (Fig. 4c). Closed wooded rangeland are limited to areas in the Atlas mountains, Albania and Greece, Sicily, Sardinia and central Spain. They have a high average tree cover (38.5%) and a high average livestock density (98.5 animals/km^2). In the remaining two systems, crop cultivation and livestock grazing occurs on the same space. The cropland and rangeland system mostly are mostly low-intensity cereal fields with livestock grazing. Such systems are present on vast areas in North-West Africa, the Iberian peninsula, the Anatolian plateau in Turkey and in the Middle East. The permanent crops and rangeland systems are present in Syria, Tunisia and Morocco (Fig. 5).

3.1.5 Settlement systems

Settlement systems occupy 5.4% of the Mediterranean region, with 4.1% being attributed to peri-urban areas, and 1.3% to urban areas. These systems have a high share of cropland cover (46 and 32% respectively), and high livestock density (78 and 51 animals/km^2 respectively). Most urban systems are found along the Mediterranean coastline, with few notable exceptions situated on the mainland (Amman, Ankara, Marrakesh, Madrid, etc.).

3.1.6 Wetlands

Wetland systems represent lakes and other wetlands that are not managed as irrigated cropland. Wetland systems are characterized by a high average value of bare cover (38.3%). Extensive salt lakes occur in the desert regions of North Africa, known as "chotts" or "sebkhas". Often they are seasonal wetlands that dry out in the summer (Khaznadar *et al.*, 2009), and are represented as deserts in land cover products. Wetlands in the Mediterranean also have a high average livestock density of 353 animals/km^2. Historically, wetlands in the MENA region have been a source of water and fodder for livestock, with numbers of livestock grazing still increasing (Houérou, 1993; Médail & Quézel, 1999).

3.2 Location factors

The results of the binominal logistic regression are summarized in Table 3 and Supplement D. Overall, we see high fits of the regression models, indicating that the selected location factors can explain a large fraction of the spatial variation in occurrence of the different land systems.

3.2.1 Bare and open grazing systems

Bare and open grazing systems generally occur in remote areas with a lower population density - with the exception of the intensive arid grazing system, that tends to occur close to markets. This system tends to occur in areas with higher solar radiation and lower potential evapotranspiration (PET). The two arid grazing systems occur in areas with low precipitation and their likelihood increases with rising altitudes.

3.2.2 Cropland systems

Cropland systems occur in areas with lower altitudes and gentle slopes. Temperature has a positive association with most cropland systems. Although these systems tend to be negatively related to population density, irrigated systems occur in areas with higher density of rural population. The location of these systems is positively related with market influence. This can be explained by the investments in the agricultural sector and the potential to sell products, which is possible in areas with a high market influence. Soil pH levels have a positive influence on the occurrence of cropland systems, whereas the soil organic content is negatively related to their occurrence.

3.2.3 Forest systems

Forest systems tend to be negatively related to population density. These systems are positively related to soil sand content, and negatively to pH levels and soil depth. When using soil characteristics based on current land cover, forest systems were positively related to organic content and soil depth. Clearly, to some extent these environmental conditions are a result of the influence of the forest ecosystem on the soil conditions itself. Forests are more frequently found on slopes and in areas with higher precipitation (except planted forests). Mediterranean natural and semi-natural forests are positively related to altitude and temperature. Planted forests are positively related to well-drained soils. While Mediterranean planted forests can consist of native species well adapted to aridity, young plantations of introduced species such as the Monterey pine (*Pinus radiata*) have higher water demands and prefer well drained soils (Garmendia *et al.*, 2012).

3.2.4 Agro-silvo-pastoral mosaics

Although mosaic systems have very different characteristics amongst the sub-types, they do have some similarities. They tend to be negatively related to population density, soil pH and soil depth. The cropland/rangeland categories have similar characteristic as cropland systems in terms of relation to slope, and have a positive association with potential evapotranspiration like intensive cropland systems. The woodland/wooded rangeland categories are similar to forest systems in terms of relations to soils characteristics, as well as to slope and precipitation. The results show that agro-silvo-pastoral mosaics resemble either cropland or forests systems in terms of location specific characteristics. This is logical, as they are either croplands, or woodlands, where other activities occur on the same space.

3.2.5 Settlement systems and wetlands

Settlement systems are, almost by definition, positively related to population density, infrastructure and market accessibility. They occur on lower altitudes with gentler slopes. Wetlands occur on flat areas with lower altitudes, and have a negative association with temperature, population density and market influence.

3.3 Performance and data uncertainty

Studies used in the validation covered the whole region (Fig. 7), although more were found in the European part (122) as compared to the MENA region (68). Out of 190 documented studies, 134 had perfect agreement (71%), 42 partial agreement (22%), and 14 were misclassified (7%), compared to our map. Studies with partial agreement had a correct identification of the land systems group, however a different land systems subgroup. The accuracies of aggregated land system categories shows the extent of inter-category misclassifications and complete misclassifications (Table 4). The producer's accuracy presents the extent of how well the documented land systems were represented on the land systems map. The user's accuracy also takes into account the extent of land systems attributed to other systems. Interestingly, our user's and producer's accuracies are in a similar range as is common for remote sensing interpretations of land cover.

Using only data with global coverage to produce the land systems map shows the drawbacks of using such data. It is difficult to differentiate between systems of different intensities and type of crops if only using proxies for intensity (Fig. 8, Supplement E). The differences are smaller for systems classified with data on bare areas, irrigation, livestock and tree cover.

When using global data, urban and peri-urban systems in the European part are overestimated (Fig. 8). All agro-silvo-pastoral mosaic systems have a low agreement between the maps, indicating that using data with global coverage significantly underestimates these areas. Mosaic systems are mostly lost on the account of more intensive cropland systems. Extensive annual cropland and all three annual-permanent mosaic systems cover significantly more areas, with permanent crop systems experiencing substantial losses. The changes are not only in terms of quantities of such systems, but mostly in their allocation, leading to a different spatial pattern (Fig. 8). Vast areas in Europe lose the fine detailed structure of cropland and agro-silvo-pastoral systems, and are represented by areas where both annual and permanent crops are cultivated (Supplement E).

4. Discussion

4.1 Classifying Mediterranean land systems

Representing the spatial pattern and intensity of human-environment interactions remains one of the most significant challenges in land systems science (Rounsevell *et al.*, 2012; Turner *et al.*, 2007). Several authors have previously combined data to improve information on land use and management. Global scale land system characterizations include those of Ellis and Ramankutty (2008) who mapped anthropogenic biomes using numerous socio-economic and bio-physical indicators. Van Asselen and Verburg (2012) mapped global land systems, and investigated their spatial determinants. Letourneau et al. (2012) classified land-use systems for use in the context of the integrated assessment model IMAGE. Václavík et al. (2013) classified land system archetypes based on similarities in a broad range of characteristics. Although recognizing similar systems on a global scale is useful for global assessments and modeling, these approaches fail to capture the diverse regional characteristics and do not always link to local systems and nomenclatures (Václavík *et al.*, 2013). On the other end of the spectrum are farming system classifications operating at the farm level, ignoring the larger landscape context, which is important for many of the services provided by these systems (Dixon *et al.*, 2001; van de Steeg *et al.*, 2010). Regional scale characterizations were made by Levers et al. (2015) and van der Zanden et al. (2016), mapping land system archetypes and cultural landscapes of Europe respectively. Levers et al. (2015) generalized Mediterranean mosaic archetypes to low intensity cropland, grassland or mosaic systems, grouping them together with low intensity single function systems. In the study of van der Zanden et al. (2016), several mosaic landscape types of different intensities were identified, however disregarding woodland systems. Our approach moved beyond existing classification systems by accounting for the specific land systems characteristic for the Mediterranean region. We identified 6 agro-silvo-pastoral classes that are all, functionally different, variations of mosaic land systems. Although the value of these mosaic systems for society and biodiversity is known, this is the first time their spatial extent and pattern is mapped.

Thresholds used in our classification are often difficult to identify and are to some extent arbitrary. For example, classifying different grazing systems is challenging, as transhumance is still significant in the Mediterranean region – livestock may only be present in an area during a particular time of the year. Sheep densities on barley fields might increase to 65 animals/ha for one month each year, in order to supplement the animals' summer diet (Correal *et al.*, 2006). In traditional continuous forage systems livestock densities are much lower, with up to 2 animals/ha (Delgado *et al.*, 2004). We focused on such systems, and did not include the temporal variability of livestock. Another example are forest systems, defined as land with over 10% tree cover by the FAO (FAO, 2000). This definition includes significant areas of woodlands hosting mosaic systems.

4.2 Uncertainties in data

Significant improvements have been made in providing global data on land cover and management intensity. Nevertheless, there are still considerable inconsistencies between different global data sets contributing to the data uncertainty (Tuanmu & Jetz, 2014). Combining different data sets derived from remote sensing, modeling or censuses can result in aggregating the inaccuracies of those data sets. As fully harmonized data on the different aspects are not available, the possible bias from inconsistencies between the different data layers is unavoidable. Sometimes, these inconsistencies reveal interesting information. We observed that the European sealed soil map defined protected agricultural areas (greenhouses) in south of Spain as sealed surfaces. This resulted in a misclassification of both the cropland and urban classes in this particular area. Although protected agriculture could be defined as a sealed surface, the same error does not occur in other regions with vast areas of protected agriculture (Greece, Italy). This prevented us from identifying protected agriculture as a separate land system using the combination of sealed or urban areas with cropland extent. Spatially explicit data on protected agriculture in the region is basically non-existent and is limited to a few areas in Italy, Israel and Spain (Aguilar *et al.*, 2015; Levin *et al.*, 2007; Picuno *et al.*, 2011).

Additional data related issues are the over- and underrepresentation of particular systems. Despite the good coverage of high resolution remote sensing derived products (Hansen *et al.*, 2013), areas covered by forests are underrepresented in the MENA region. Our analysis has shown a potential overestimation of intensive, and underestimation of mosaic land systems in the data poor parts of the Mediterranean (Fig. 8, Supplement E).

In terms of agricultural and forest management intensity, there is inadequate global data, or it is not available at sufficiently detailed spatial resolution (Hurtt *et al.*, 2006; Ramankutty *et al.*, 2008). To identify the intensity of Mediterranean land systems, we had to use a set of different proxies. Our combination of field size and yield used in the non-European part of the region did not consider the numerous aspects of both the input and output intensities (Erb *et al.*, 2013). Yields and management are varying with time and incorporating multi-temporal data could improve the identification of management intensity (Levers *et al.*, 2015). Similar concerns hold for forest management. Although we used temporal changes in forest cover as a proxy for forest management for the non-European Mediterranean part, other data such as wood production and socio-economic statistics could be helpful (Verkerk *et al.*, 2015).

This study presents a novel data assimilation approach to identify the extent and spatial patterns of Mediterranean land systems. As land systems are composed of different components, their characteristics will never be measured and observed by single sensors. Combining different datasets will, therefore, always be needed to update the map in the future.

4.3 Application of results

The resulting land systems map has a wide potential of use. The identified extent of agro-silvo-pastoral mosaics can be used for prioritization of landscapes for biodiversity and cultural heritage conservation. The results can also be used in earth system modeling, as using land systems in such models can provide a more accurate representation of the intensity of human-environment interactions (van Asselen & Verburg, 2012). When modeling climate impacts, using such a map can provide more information. For example, the albedo and greenhouse gas emissions and sequestration will be different between the systems. The results can also be used in land-change models or in integrated assessment models, to analyze consequences of future socio-economic changes (Verburg *et al.*, 2011a). Using land systems we can capture changes in management intensity, as socio-economic changes often do not affect land cover directly.

To improve our approach, better data is needed for the Middle Eastern and North African part of the region. Vast areas of extensive cropland and agro-silvo-pastoral mosaic systems are present there, significant for regional food security and biodiversity. These areas are also more representative for other cropland and woodland areas in semi-arid regions.

5. Conclusion

Mediterranean landscapes have been shaped through centuries by human activities in often harsh environmental conditions. This has resulted in diverse land systems with high cultural values and of high importance for regional food production. Our typology provides a first map that represents diverse land systems, including multifunctional landscapes and other aspects of land management in the Mediterranean region that have been widely studied but not represented in maps. This typology helps to improve the understanding of Mediterranean land systems and is a basis for assessments of future changes in regional climate, land use and land cover change and changes in management intensity. Compared to existing global and regional classifications our typology significantly improved the thematic resolution and particularly was able to represent agro-silvo-pastoral mosaic systems, which were mostly represented as single function low intensity grassland or cropland in other studies. The comparison with case studies throughout the region has shown that our map sufficiently well represents the variation in land systems across the region and, thus, can be used to support prioritization of areas for biodiversity protection, conservation of cultural landscapes, or food production.

References

Agnoletti M (2014) Rural landscape, nature conservation and culture: Some notes on research trends and management approaches from a (southern) European perspective. *Landscape and Urban Planning*, **126**, 66–73. doi - 10.1016/j.landurbplan.2014.02.012

Aguilar MA, Vallario A, Aguilar FJ, Lorca AG, Parente C (2015) Object-Based Greenhouse Horticultural Crop Identification from Multi-Temporal Satellite Imagery: A Case Study in Almeria, Spain. *Remote Sensing*, **7**, 7378–7401. doi - 10.3390/rs70607378

Almagro M, Vente J de, Boix-Fayos C et al. (2013) Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems. *Mitigation and Adaptation Strategies for Global Change*, 1–15. doi - 10.1007/s11027-013-9535-2

Almeida M, Guerra C, Pinto-Correia T (2013) Unfolding relations between land cover and farm management: high nature value assessment in complex silvo-pastoral systems. *Geografisk Tidsskrift-Danish Journal of Geography*, **113**, 97–108. doi - 10.1080/00167223.2013.848611

van Asselen S, Verburg PH (2012) A Land System representation for global assessments and land-use modeling. *Global Change Biology*, **18**, 3125–3148. doi - 10.1111/j.1365-2486.2012.02759.x

Blanchard SD, Pontius Jr. RG, Urban KM (2015) Implications of Using 2 m versus 30 m Spatial Resolution Data for Suburban Residential Land Change Modeling. *Journal of Environmental Informatics*. doi - 10.3808/jei.201400284

Britz W, Witzke P (2014) *Common Agricultural Policy regionalised Impact Modelling System (CAPRI). Modelling System Documentation.* Bonn.

Brus DJ, Hengeveld GM, Walvoort DJJ, Goedhart PW, Heidema AH, Nabuurs GJ, Gunia K (2012) Statistical mapping of tree species over Europe. *European Journal of Forest Research*, **131**, 145–157. doi - 10.1007/s10342-011-0513-5

Bunce RGH, Pérez-Soba M, Smith M (2008) Assessment of the Extent of Agroforestry Systems in Europe and Their Role Within Transhumance Systems. In: *Agroforestry in Europe: Current Status and Future Prospects* (eds Rodríguez AR, McAdam J, Mosquera-Losada MR). Springer Science & Business Media.

CIESIN (2015) Gridded Population of the World, Version 4. Center for International Earth Science Information Network - CIESIN - Columbia University. NASA Socioeconomic Data and Applications Center (SEDAC).

CIESIN, IFPRI, CIAT (2011) Global Rural-Urban Mapping Project, Version 1: Population Density Grid. Center for International Earth Science Information Network - CIESIN - Columbia University, International Food Policy Research Institute - IFPRI, The World Bank, and Centro Internacional de Agricultura Tropical - CIAT.

Correal E, Robledo A, Rios S, Rivera D (2006) Mediterranean dryland mixed sheep-cereal systems. *Grassland Science in Europe*, **11**, 14–26.

Cuttelod A, Garcia N, Malak DA, Temple HJ, Katariya V (2009) The Mediterranean: a biodiversity hotspot under threat. In: *Wildlife in a Changing World: An Analysis of the 2008 IUCN Red List of Threatened Species* (eds Vie J-C, Hilton-Taylor C, Stuart SN). International Union for Conservation of Nature, Gland, Switzerland.

Daccache A, Ciurana JS, Diaz JAR, Knox JW (2014) Water and energy footprint of irrigated agriculture in the Mediterranean region. *Environmental Research Letters*, **9**, 124014. doi - 10.1088/1748-9326/9/12/124014

van Delden H, van Vliet J, Rutledge DT, Kirkby MJ (2011) Comparison of scale and scaling issues in integrated land-use models for policy support. *Agriculture, Ecosystems & Environment*, **142**, 18–28. doi - 10.1016/j.agee.2011.03.005

Delgado I, Andueza D, Muñoz F, Lahoz F (2004) Forage system to replace marginal rainfed cereal areas by sheep production. An experimental study. *Options Méditerranéennes. Serie A*, **60**, 263–266.

Dixon J, Gulliver A, Gibbon D, Hall M (2001) *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World.* FAO and World Bank, Rome and Washington D.C.

EEA (2015a) CORINE Land Cover 2006 — Copernicus Land Monitoring Services.

EEA (2015b) Imperviousness Soil Sealing High Resolution Data. Copernicus Land Monitoring Services. European Environment Agency.

Ellis EC, Ramankutty N (2008) Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, **6**, 439–447. doi - 10.1890/070062

Erb K-H, Haberl H, Jepsen MR et al. (2013) A conceptual framework for analysing and measuring land-use intensity. *Current Opinion in Environmental Sustainability*, **5**, 464–470. doi - 10.1016/j.cosust.2013.07.010

Evans JP (2008) 21st century climate change in the Middle East. *Climatic Change*, **92**, 417–432. doi - 10.1007/s10584-008-9438-5

Fader M, Shi S, von Bloh W, Bondeau A, Cramer W (2016) Mediterranean irrigation under climate change: more efficient irrigation needed to compensate increases in irrigation water requirements. *Hydrology and Earth System Sciences*, **20**, 953–973. doi - 10.5194/hess-20-953-2016

FAO (2000) *Global Forest Resource Assessment 2000 – Main Report, FAO Forestry Paper 140*. United Nations Food and Agricultural Organization, Rome.

FAO (2011) *Land Degradation Assessment in Drylands. Mapping Land Use Systems at Global and Regional Scales for Land Degradation Assessment Analysis. Version 1.1*. FAO, Rome.

Fritz S, See L, McCallum I et al. (2015) Mapping global cropland and field size. *Global Change Biology*, **21**, 1980–1992. doi - 10.1111/gcb.12838

Fuchs R, Herold M, Verburg PH, Clevers JGPW (2013) A high-resolution and harmonized model approach for reconstructing and analysing historic land changes in Europe. *Biogeosciences*, **10**, 1543–1559. doi - 10.5194/bg-10-1543-2013

García-Llorente M, Martín-López B, Iniesta-Arandia I, López-Santiago CA, Aguilera PA, Montes C (2012) The role of multi-functionality in social preferences toward semi-arid rural landscapes: An ecosystem service approach. *Environmental Science & Policy*, **19**–**20**, 136–146. doi - 10.1016/j.envsci.2012.01.006

Garmendia E, Mariel P, Tamayo I, Aizpuru I, Zabaleta A (2012) Assessing the effect of alternative land uses in the provision of water resources: Evidence and policy implications from southern Europe. *Land Use Policy*, **29**, 761–770. doi - 10.1016/j.landusepol.2011.12.001

Guerra CA, Metzger MJ, Maes J, Pinto-Correia T (2015) Policy impacts on regulating ecosystem services: looking at the implications of 60 years of landscape change on soil erosion prevention in a Mediterranean silvo-pastoral system. *Landscape Ecology*, 1–20. doi - 10.1007/s10980-015-0241-1

Hansen MC, Potapov PV, Moore R et al. (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**, 850–853. doi - 10.1126/science.1244693

Hengeveld GM, Nabuurs G-J, Didion M, van den Wyngaert I, Clerkx APPM, Schelhaas M-J (2012) A Forest Management Map of European Forests. *Ecology and Society*, **17**. doi - 10.5751/ES-05149-170453

Hengl T, de Jesus JM, MacMillan RA et al. (2014) SoilGrids1km — Global Soil Information Based on Automated Mapping. *PLoS ONE*, **9**, e105992. doi - 10.1371/journal.pone.0105992

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, **25**, 1965–1978. doi - 10.1002/joc.1276

Houérou HNL (1993) Salt-tolerant plants for the arid regions of the Mediterranean isoclimatic zone. In: *Towards the rational use of high salinity tolerant plants* (eds Lieth H, Masoom AAA), pp. 403–422. Springer Netherlands. doi - 10.1007/978-94-011-1858-3_42

Huld T, Müller R, Gambardella A (2012) A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy*, **86**, 1803–1815. doi - 10.1016/j.solener.2012.03.006

Hurtt GC, Frolking S, Fearon MG et al. (2006) The underpinnings of land-use history: three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Global Change Biology*, **12**, 1208–1229. doi - 10.1111/j.1365-2486.2006.01150.x
IUCN (2015) World Database on Protected Areas.
Joffre R, Rambal S, Ratte JP (1999) The dehesa system of southern Spain and Portugal as a natural ecosystem mimic. *Agroforestry Systems*, **45**, 57–79. doi - 10.1023/A:1006259402496
Jun C, Ban Y, Li S (2014) China: Open access to Earth land-cover map. *Nature*, **514**, 434–434. doi - 10.1038/514434c
Khaznadar M, Vogiatzakis IN, Griffiths GH (2009) Land degradation and vegetation distribution in Chott El Beida wetland, Algeria. *Journal of Arid Environments*, **73**, 369–377. doi - 10.1016/j.jaridenv.2008.09.026
Kuemmerle T, Erb K, Meyfroidt P et al. (2013) Challenges and opportunities in mapping land use intensity globally. *Current Opinion in Environmental Sustainability*, **5**, 484–493. doi - 10.1016/j.cosust.2013.06.002
Lambin EF, Turner BL, Geist HJ et al. (2001) The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change*, **11**, 261–269. doi - 10.1016/S0959-3780(01)00007-3
Latham J, Cumani R, Rosati I, Bloise M (2014) *Global Land Cover SHARE Database Beta-Release Version 1.0*. FAO, Rome.
Letourneau A, Verburg PH, Stehfest E (2012) A land-use systems approach to represent land-use dynamics at continental and global scales. *Environmental Modelling & Software*, **33**, 61–79. doi - 10.1016/j.envsoft.2012.01.007
Levers C, Müller D, Erb K et al. (2015) Archetypical patterns and trajectories of land systems in Europe. *Regional Environmental Change*, 1–18. doi - 10.1007/s10113-015-0907-x
Levin N, Lugassi R, Ramon U, Braun O, Ben-Dor E (2007) Remote sensing as a tool for monitoring plasticulture in agricultural landscapes. *International Journal of Remote Sensing*, **28**, 183–202. doi - 10.1080/01431160600658156
Médail F, Quézel P (1999) Biodiversity Hotspots in the Mediterranean Basin: Setting Global Conservation Priorities. *Conservation Biology*, **13**, 1510–1513. doi - 10.1046/j.1523-1739.1999.98467.x
Meeus JHA (1995) Pan-European landscapes. *Landscape and Urban Planning*, **31**, 57–79. doi - 10.1016/0169-2046(94)01036-8
Neumann K, Sietz D, Hilderink H, Janssen P, Kok M, van Dijk H (2015) Environmental drivers of human migration in drylands – A spatial picture. *Applied Geography*, **56**, 116–126. doi - 10.1016/j.apgeog.2014.11.021
NGIA (2015) VMap0 data. National Geosptial Intelligence Agency. http://gis-lab.info/qa/vmap0-eng.html.
Nieto-Romero M, Oteros-Rozas E, González JA, Martín-López B (2014) Exploring the knowledge landscape of ecosystem services assessments in Mediterranean agroecosystems: Insights for future research. *Environmental Science & Policy*, **37**, 121–133. doi - 10.1016/j.envsci.2013.09.003
Olson DM, Dinerstein E, Wikramanayake ED et al. (2001) Terrestrial Ecoregions of the World: A New Map of Life on Earth A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience*, **51**, 933–938.
Panagos P, Hiederer R, Van Liedekerke M, Bampa F (2013) Estimating soil organic carbon in Europe based on data collected through an European network. *Ecological Indicators*, **24**, 439–450. doi - 10.1016/j.ecolind.2012.07.020
Pfeiffer T, Koutantou A (2015) Greece debt crisis: Olive oil supplies threatened as banking system grinds to a halt. *The Independent*.
Pickett STA, Cadenasso ML (1995) Landscape Ecology: Spatial Heterogeneity in Ecological Systems. *Science*, **269**, 331–334. doi - 10.1126/science.269.5222.331

Picuno P, Tortora A, Capobianco RL (2011) Analysis of plasticulture landscapes in Southern Italy through remote sensing and solid modelling techniques. *Landscape and Urban Planning*, **100**, 45–56. doi - 10.1016/j.landurbplan.2010.11.008

Plieninger T, Schaar M (2008) Modification of Land Cover in a Traditional Agroforestry System in Spain: Processes of Tree Expansion and Regression. *Ecology and Society*, **13**.

Pontius RG, Santacruz A (2014) Quantity, exchange, and shift components of difference in a square contingency table. *International Journal of Remote Sensing*, **35**, 7543–7554. doi - 10.1080/2150704X.2014.969814

Ramankutty N, Evan AT, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000: Global Agricultural Lands in 2000. *Global Biogeochemical Cycles*, **22**. doi - 10.1029/2007GB002952

Robinson TP, Wint GRW, Conchedda G et al. (2014) Mapping the Global Distribution of Livestock. *PLoS ONE*, **9**, e96084. doi - 10.1371/journal.pone.0096084

Rodríguez C, Wiegand K (2009) Evaluating the trade-off between machinery efficiency and loss of biodiversity-friendly habitats in arable landscapes: The role of field size. *Agriculture, Ecosystems & Environment*, **129**, 361–366. doi - 10.1016/j.agee.2008.10.010

Rounsevell MDA, Pedroli B, Erb K-H et al. (2012) Challenges for land system science. *Land Use Policy*, **29**, 899–910. doi - 10.1016/j.landusepol.2012.01.007

Schröter D, Cramer W, Leemans R et al. (2005) Ecosystem Service Supply and Vulnerability to Global Change in Europe. *Science*, **310**, 1333–1337. doi - 10.1126/science.1115233

Siebert S, Döll P, Hoogeveen J, Faures J-M, Frenken K, Feick S (2005) Development and validation of the global map of irrigation areas. *Hydrology and Earth System Sciences*, **9**, 535–547. doi - 10.5194/hess-9-535-2005

Siebert S, Henrich V, Frenken K, Burke J (2013) Update of the digital global map of irrigation areas to version 5. Rheinische Friedrich-Wilhelms-Universität, Bonn, Germany and FAO, Rome, Italy, 170pp.

Sowers J, Vengosh A, Weinthal E (2010) Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climatic Change*, **104**, 599–627. doi - 10.1007/s10584-010-9835-4

van de Steeg JA, Verburg PH, Baltenweck I, Staal SJ (2010) Characterization of the spatial distribution of farming systems in the Kenyan Highlands. *Applied Geography*, **30**, 239–253. doi - 10.1016/j.apgeog.2009.05.005

Stoorvogel JJ, Bakkenes M, Temme AJAM, Batjes NH, ten Brink B (2016) S-World: a Global Soil Map for Environmental Modelling: S-World: a Global Soil Map for Environmental Modelling. *Land Degradation & Development*, **28**, 22-33. doi - 10.1002/ldr.2656

Temme AJAM, Verburg PH (2011) Mapping and modelling of changes in agricultural intensity in Europe. *Agriculture, Ecosystems & Environment*, **140**, 46–56. doi - 10.1016/j.agee.2010.11.010

Tuanmu M-N, Jetz W (2014) A global 1-km consensus land-cover product for biodiversity and ecosystem modelling. *Global Ecology and Biogeography*, **23**, 1031–1045. doi - 10.1111/geb.12182

Turner BL, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences*, **104**, 20666–20671. doi - 10.1073/pnas.0704119104

Václavík T, Lautenbach S, Kuemmerle T, Seppelt R (2013) Mapping global land system archetypes. *Global Environmental Change*, **23**, 1637–1647. doi - 10.1016/j.gloenvcha.2013.09.004

Verburg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SSA (2002) Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. *Environmental Management*, **30**, 391–405. doi - 10.1007/s00267-002-2630-x

Verburg PH, Neumann K, Nol L (2011a) Challenges in using land use and land cover data for global change studies. *Global Change Biology*, **17**, 974–989. doi - 10.1111/j.1365-2486.2010.02307.x

Verburg PH, Ellis EC, Letourneau A (2011b) A global assessment of market accessibility and market influence for global environmental change studies. *Environmental Research Letters*, **6**, 34019. doi - 10.1088/1748-9326/6/3/034019

Verkerk PJ, Levers C, Kuemmerle T, Lindner M, Valbuena R, Verburg PH, Zudin S (2015) Mapping wood production in European forests. *Forest Ecology and Management*, **357**, 228–238. doi - 10.1016/j.foreco.2015.08.007

Wright B, Cafiero C (2011) Grain reserves and food security in the Middle East and North Africa. *Food Security*, **3**, 61–76. doi - 10.1007/s12571-010-0094-z

WWF (2004) Global Lakes and Wetlands Database. *World Wildlife Fund*.

You L, Wood-Sichra U, Fritz S, Guo Z, See L, Koo L (2014) Spatial Production Allocation Model (SPAM) 2005 v2.0.

Zamora J, Verdú JR, Galante E (2007) Species richness in Mediterranean agroecosystems: Spatial and temporal analysis for biodiversity conservation. *Biological Conservation*, **134**, 113–121. doi - 10.1016/j.biocon.2006.08.011

van der Zanden EH, Levers C, Verburg PH, Kuemmerle T (2016) Representing composition, spatial structure and management intensity of European agricultural landscapes: A new typology. *Landscape and Urban Planning*, **150**, 36–49. doi - 10.1016/j.landurbplan.2016.02.005

Zomer RJ, Trabucco A, Bossio DA, Verchot LV (2008) Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment*, **126**, 67–80. doi - 10.1016/j.agee.2008.01.014

Zomer RJ, Trabucco A, Coe R, Place F (2009) *Trees on farm: analysis of global extent and geographical patterns of agroforestry*. World Agroforestry Centre, Nairobi, Kenya.

List of tables

Table 1. Data used in the hierarchical classification

Group	Description	Original resolution	Spatial, temporal coverage	Unit	Source
Forest	Tree cover	30 m	Whole area, 2000 - 2014	%	Hansen et al. (2013)
	Tree cover gain and loss	30 m	Whole area, 2000 - 2014	presence	Hansen et al. (2013)
	Tree cover loss and gain ratio	30 m	Whole area, 2000 - 2014	%	Derived from Hansen et al. (2013)
	European forest management types	1 km	Europe, 2010	class	Hengeveld et al. (2012)
	Plantation tree species occurrence (*Eucalyptus* spp., *Populous* spp., *Pinus* spp., *Robinia* spp.)	1 km	Europe, 2000-2010	class	Brus et al. (2012)
Bare and artificial	Bare areas	30 m	Whole area, 2010	%	Latham et al. (2014)
	Built up areas	30 m	Whole area, 2010	%	Jun et al. (2014)
	Imperviousness	25 m	Europe, 2010	%	EEA (2015b)
Livestock and cropland	Cropland extent	1 km	Whole area, 2014	%	Fritz et al. (2015)
	Livestock density (bovines, goats and sheep)	1 km	Whole area, 2014	nr./ km^2	Robinson et al. (2014)
	Area equipped for irrigation	1 km	Whole area, 2006	ha	Siebert et al. (2013)
	European crop type map	vector	EU27, 2006	%	Britz and Witzke (2014)
	CORINE permanent crop land cover (vineyards, orchards, olive groves)	100 m	Non EU Europe and Turkey, 2006	class	EEA (2015a)
	SPAM permanent crop extent (oil, fruit, tropical fruit)	10 km	MENA, 2014	%	You et al. (2014)
	Fertilizer intensity	1 km	EU 27, 2000	class	Temme and Verburg (2011)
	Field size map	1 km	Whole area, 2015	class	Fritz et al. (2015)
	Areas with highest annual crop yield 10^{th} quantile of yields as intensification qualifies	MENA, Turkey	10 km, 2010	t/ha	You et al. (2014)
	Areas with highest permanent crop yields (olives, temperate and tropic fruits) – 10^{th} quantile of yields as intensification qualifies	Non EU Europe, MENA, Turkey	10 km, 2010	t/ha	You et al. (2014)
Other	Wetlands and lakes	250 m	Whole area, 2004	class	WWF (2004)
	Terrestrial ecoregions	vector	Whole area, 2001	class	Olson et al. (2001)
	Protected areas	vector	Whole area, 2001	class	IUCN (2015)

Table 2: Location factors used in the regression analyses

Location Factor	Unit/description	Resolution	Date	Source
Socio-economic				
Population density	People/km^2	1 km	2010	CIESIN (2015)
Rural population	Rural population/km^2	1 km	2000	CIESIN et al. (2011)
Market accessibility	Index (0-1)	1 km	2000-2010	Verburg et al. (2011b)
Market influence	USD/person (ppp)	1 km	2000-2010	Verburg et al. (2011b)
Accessibility	Distance to roads (m)	vector	1999	NGIA (2015)
Soil				
Drainage	Drainage class	1 km	2010	Hengl et al. (2014)
Sand content	Sand mass in %	1 km	2010	Stoorvogel (2016)
Clay content	Clay mass in %	1 km	2013	Stoorvogel (2016)
Cation Exchange Capacity (CEC)	cmol/kg	1 km	2010	Hengl et al. (2014)
pH	log(h+)	1 km	2010	Hengl et al. (2014)
Organic carbon content	g/kg in the top 50 cm	1 km	2013	Stoorvogel (2016)
Soil depth	cm	1 km	2013	Stoorvogel (2016)
Terrain				
Altitude	m above sea level	1 km	2005	Hijmans et al. (2005)
Slope	Slope degrees	1 km	2005	derived from Hijmans et al. (2005)
Climate				
Precipitation	annual precipitation (sum of monthly means) in mm	1 km	2005	Hijmans et al. (2005)
Temperature	Temperature (mean of monthly means) Celsius degree	1 km	2005	Hijmans et al. (2005)
Solar radiation	Horizontal surface irradiation (kWh/m^2), 1998-2011 mean	1.5 arc minute	2012	Huld et al. (2012)
Other				
Potential Evapotranspiration (PET)	annual PET in mm	1 km	2007	Zomer et al. (2008)
Potential vegetation	Pot. vegetation classes	10 km	2010	Ellis & Ramankutty (2008)

Table 3: Regression coefficients for most significant Mediterranean land systems (full regression table in Supplement D; all coefficients significant at values below the 0.05 significance level)

	Intensive arid grazing	**Wetlands**	**Open wooded rangeland**	**Closed wooded rangeland**	**Extensive ann. cropland**	**Irrigated perm. crops**	**(semi) natural forest**	**Urban**
Constant	-7.34	-0.38	-17.36	7.51	-1.20	-5.51	10.02	-0.20
Socio-economic								
Population density	-1.46E-3	-7.69E-4	-1.20E-3	-1.57E-3	-8.9E-4		-2.37E-3	3.86E-3
Rural population	-1.75E-3		-1.79E-3				-2.93E-3	-6.47E-3
Market accessibility	2.32		-3.11E-1	-4.40E-1	1.64	-2.30		1.53
Market influence	-2.50E-2	-1.57E-2			-1.735E-2	2.39E-2		
Road distance	-1.86E-5	2.00E-5			-3.08E-5	-8.64E-5		-2.90E-4
Soil characteristics								
Sand					1.91E-2		3.18E-2	
Clay		5.33E-2	-2.52E-2	-3.29E-2	3.32E-2			
CEC		5.34E-2	-1.90E-2		1.66E-2			
pH	1.63E-1		-3.39E-1		2.19E-1	2.80E-1	-3.00E-1	
Organic content	-5.36E-3	-8.42E-2			-8.57E-3	-7.35E-3		
Soil depth			-9.12E-3	-8.35E-3			-1.52E-2	
Drainage*		-1.50E-1 (b)						
Terrain								
Altitude	1.39E-3	-1.78E-3	-3.20E-4		3.90E-4	-6.72E-4	1.70E-3	-1.35E-3
Slope	7.64E-2	-4.88E-1	1.25E-1	1.25E-1		-1.93E-1	1.05E-1	-1.75E-1
Climate								
Precipitation	-2.91E-3		1.14E-3	2.85E-3	-2.56E-3			
Temperature		-1.38E-1		1.87E-1		4.59E-1	4.13E-1	
Solar radiation	4.79E-3	3.72E-3		-4.58E-3		-1.79E-3	-5.43E-3	
Other								
PET	-1.78E-3				-1.97E-3		-5.26E-3	
Potential natural vegetation**			-2.33 (7) -1.85 (9) 3.98 (10)		2.04 (2) 3.11 (4) 1.99 (6) 2.59 (7)	-1.98 (7) -2.02 (10)	-4.47 (4) -4.09 (7) 4.68 (9)	
ROC	0.86	0.92	0.82	0.84	0.75	0.87	0.90	0.94

*Drainage classes: scale from a to g; a = poorly drained, g = excessively drained

**Potential natural vegetation: 2 = tropical deciduous woodland, 3 = temperate evergreen woodland, 6 = mixed woodland, 7 = savanna, 8 = grassland and steppe, 9 = dense shrubland, 10 = open shrubland

Table 4: Shares of documented land system locations with perfect and partial agreement, and misclassification in %, together with the producer's and user's accuracy of the classification for aggregated land system categories

Land system category	Perfect	Partial	Misclassification	Producer's accuracy	User's accuracy
Rangeland and grazing	56.5	26.1	17.4	66.7	88.9
Cropland	74.0	16.9	9.1	93.6	89.0
Forest	75.0	21.4	3.6	85.7	88.9
Agro-silvo-pastoral mosaics	69.2	28.9	1.9	84.6	87.8
(peri)Urban	100.0	0.0	0.0	100.0	61.5

List of figures

List of appendices

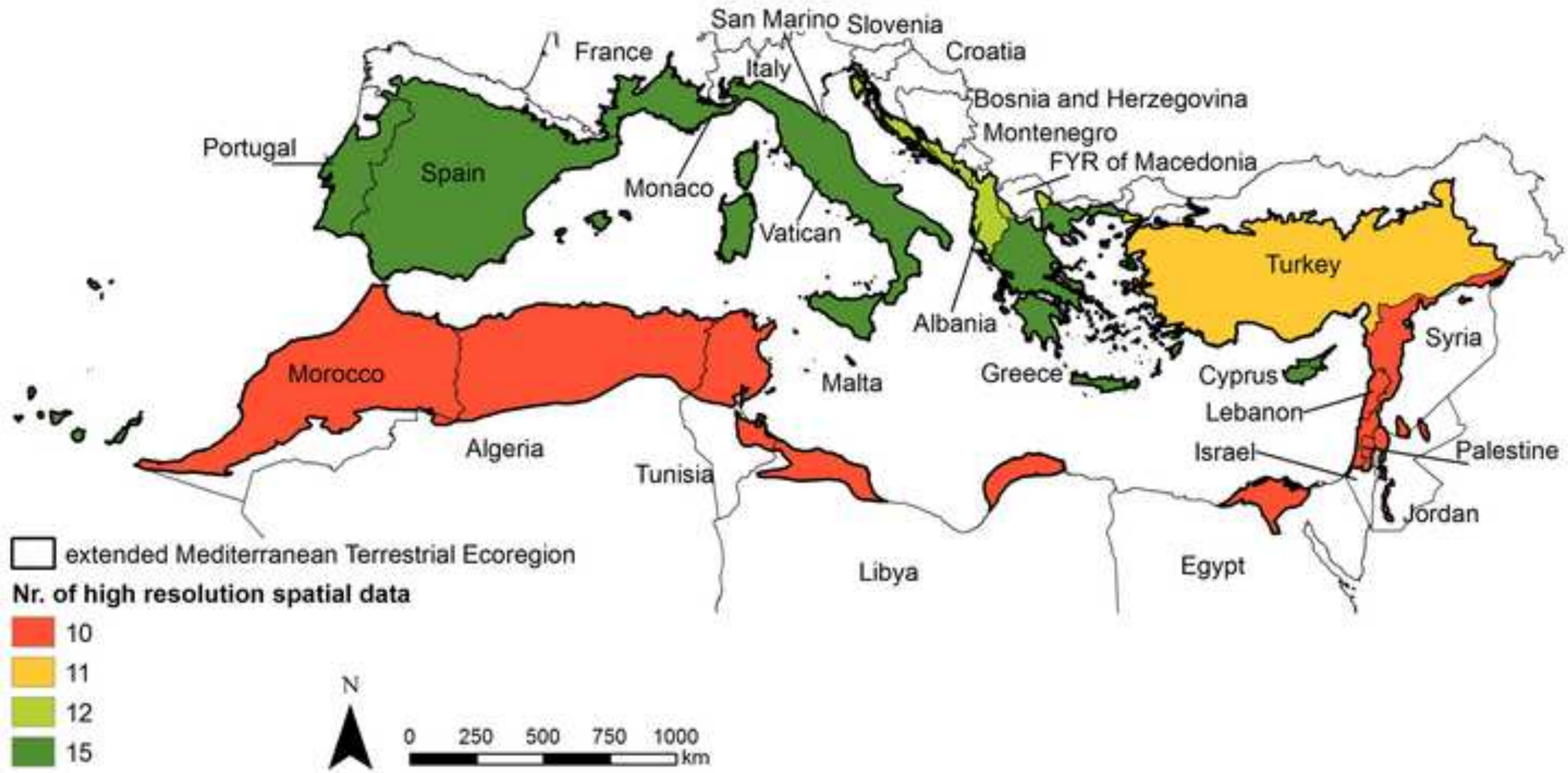
Supplement A: Classification details per land system

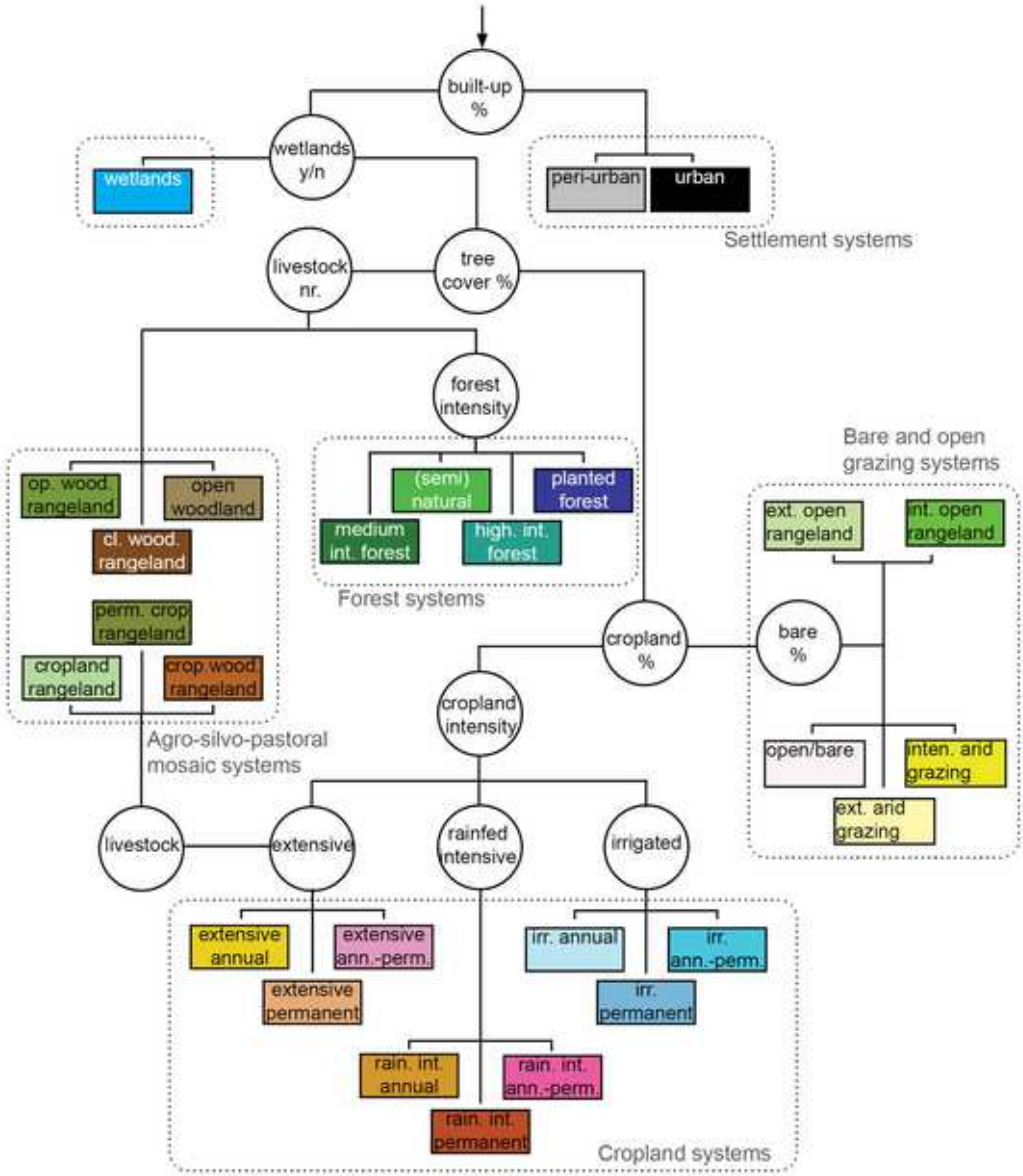
Supplement B: Studies used in the documented land systems validation per country

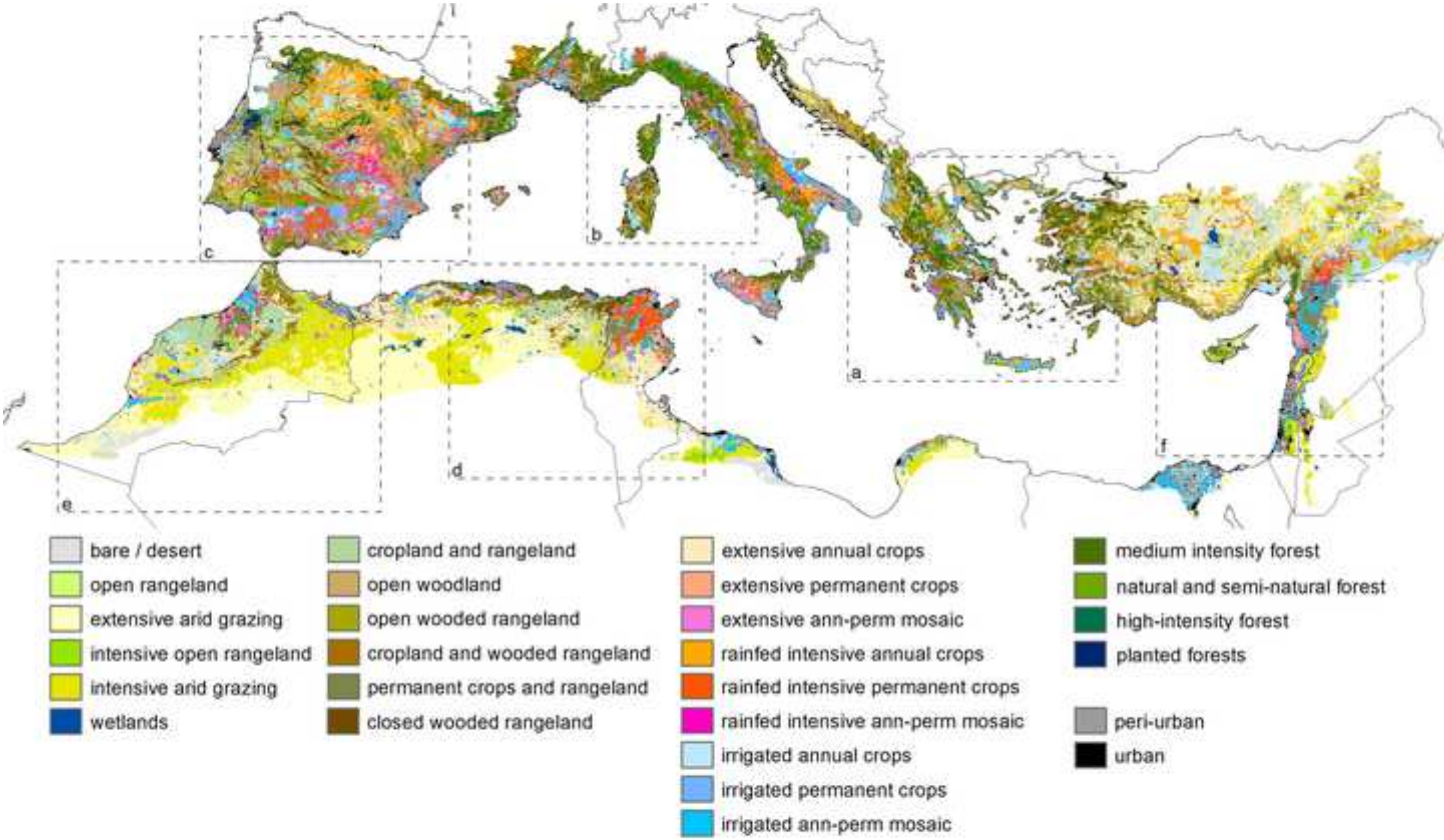
Supplement C: Average values for cropland, tree and bare cover, and livestock density per land system, standard deviations in brackets

Supplement D: Logistic regression results. All coefficients significant at values below the 0.05 significance level

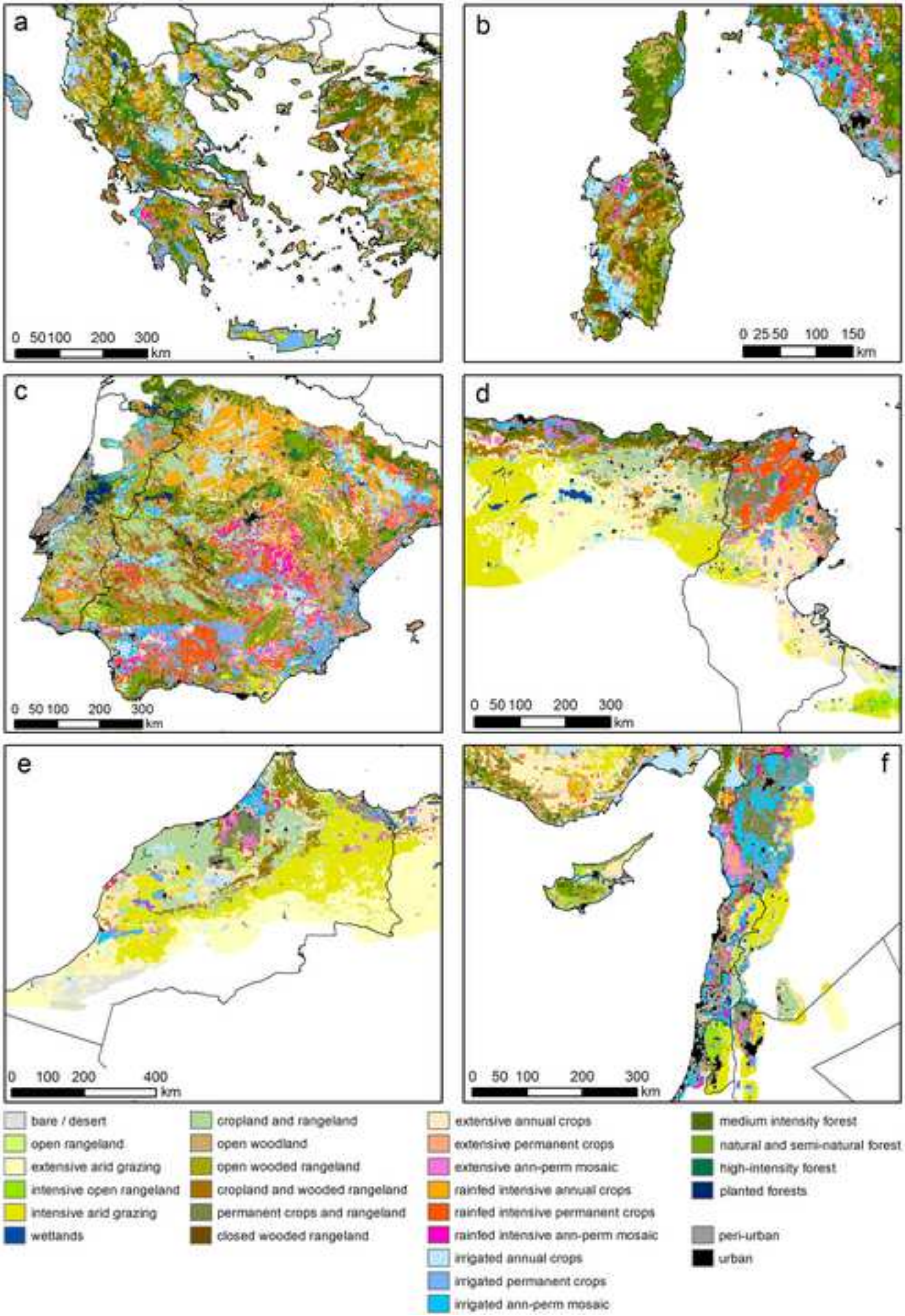
Supplement E: Mediterranean land systems map generated using globally available data

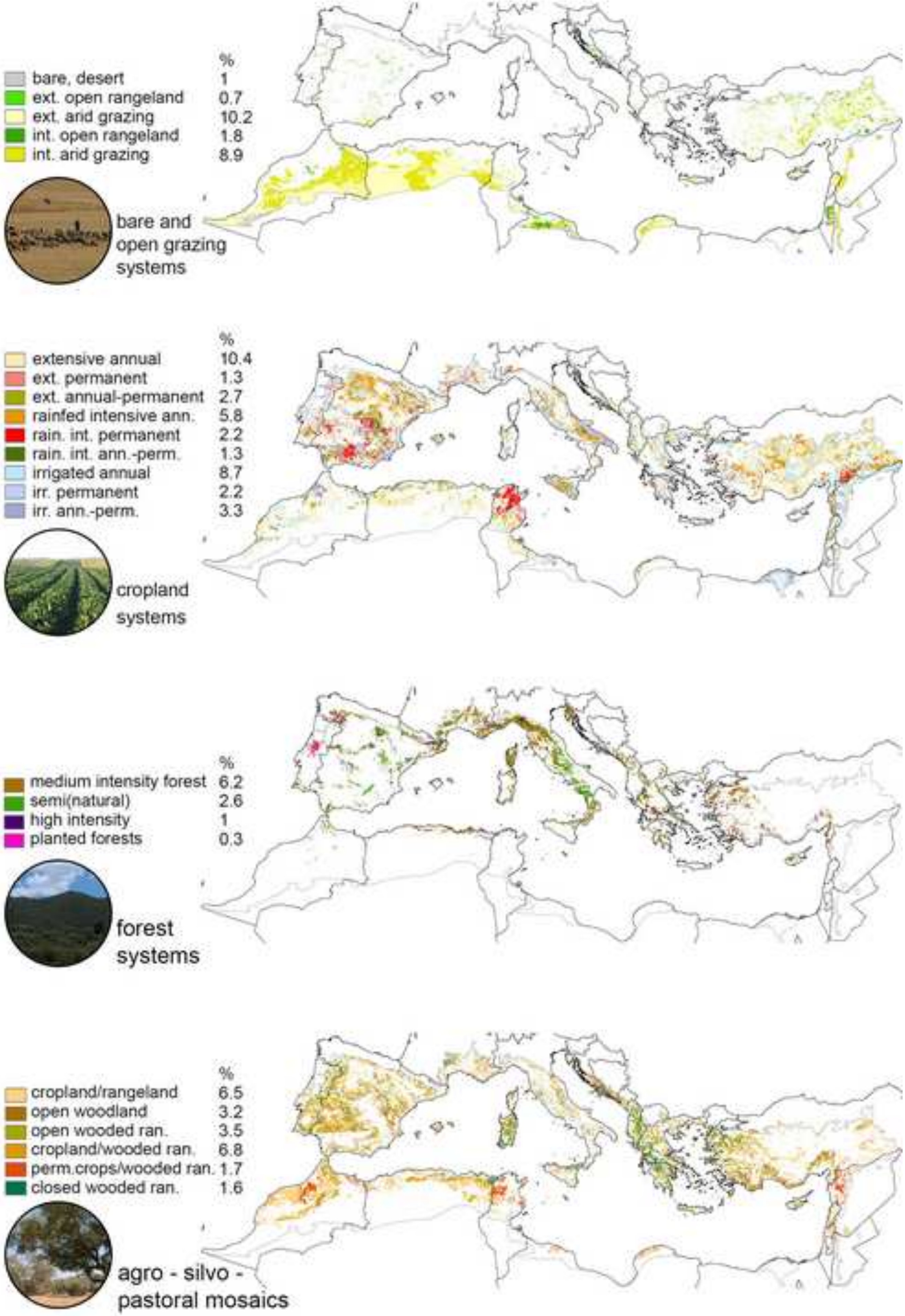

San Marino
Slovenia
France
Croatia
Italy
Bosnia and Herzegovina
Portugal
Montenegro
FYR of Macedonia
Spain
Monaco
Vatican
Turkey
Albania
Syria
Morocco
Malta
Greece
Cyprus
Lebanon
Algeria
Israel
Palestine
Tunisia
Jordan
Libya
Egypt
extended Mediterranean Terrestrial Ecoregion
Nr. of high resolution spatial data
10
11
12
15
N
0 250 500 750 1000
km

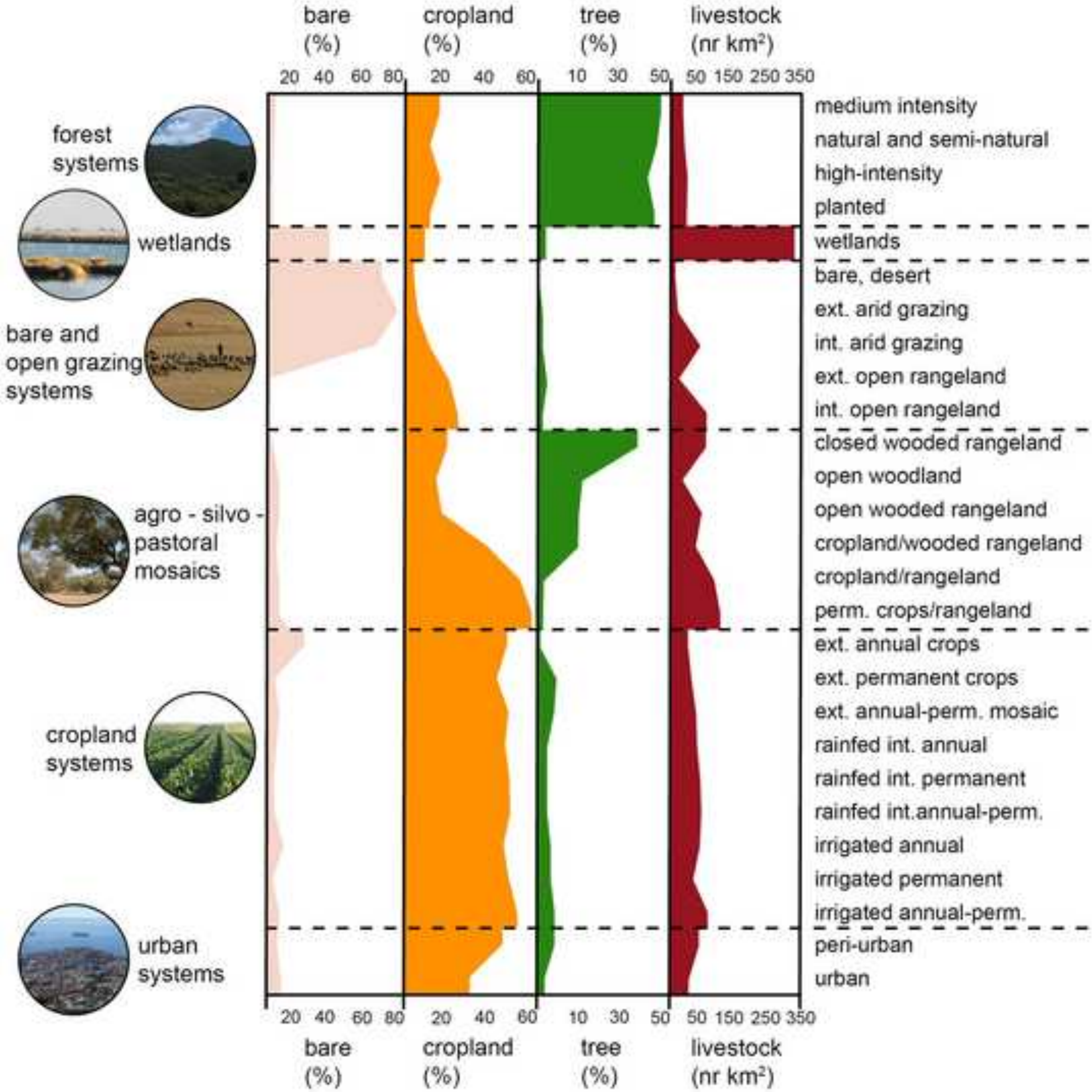

built-up %
wetlands y/n
wetlands
peri-urban
urban
Settlement systems
livestock nr.
tree cover %
forest intensity
op. wood. rangeland
open woodland
cl. wood. rangeland
perm. crop rangeland
cropland rangeland
crop.wood rangeland
Agro-silvo-pastoral mosaic systems
(semi) natural
planted forest
medium int. forest
high. int. forest
Forest systems
Bare and open grazing systems
ext. open rangeland
int. open rangeland
cropland %
bare %
open/bare
inten. arid grazing
ext. arid grazing
cropland intensity
livestock
extensive
rainfed intensive
irrigated
extensive annual
extensive ann.-perm.
extensive permanent
irr. annual
irr. ann.-perm.
irr. permanent
rain. int. annual
rain. int. ann.-perm.
rain. int. permanent
Cropland systems



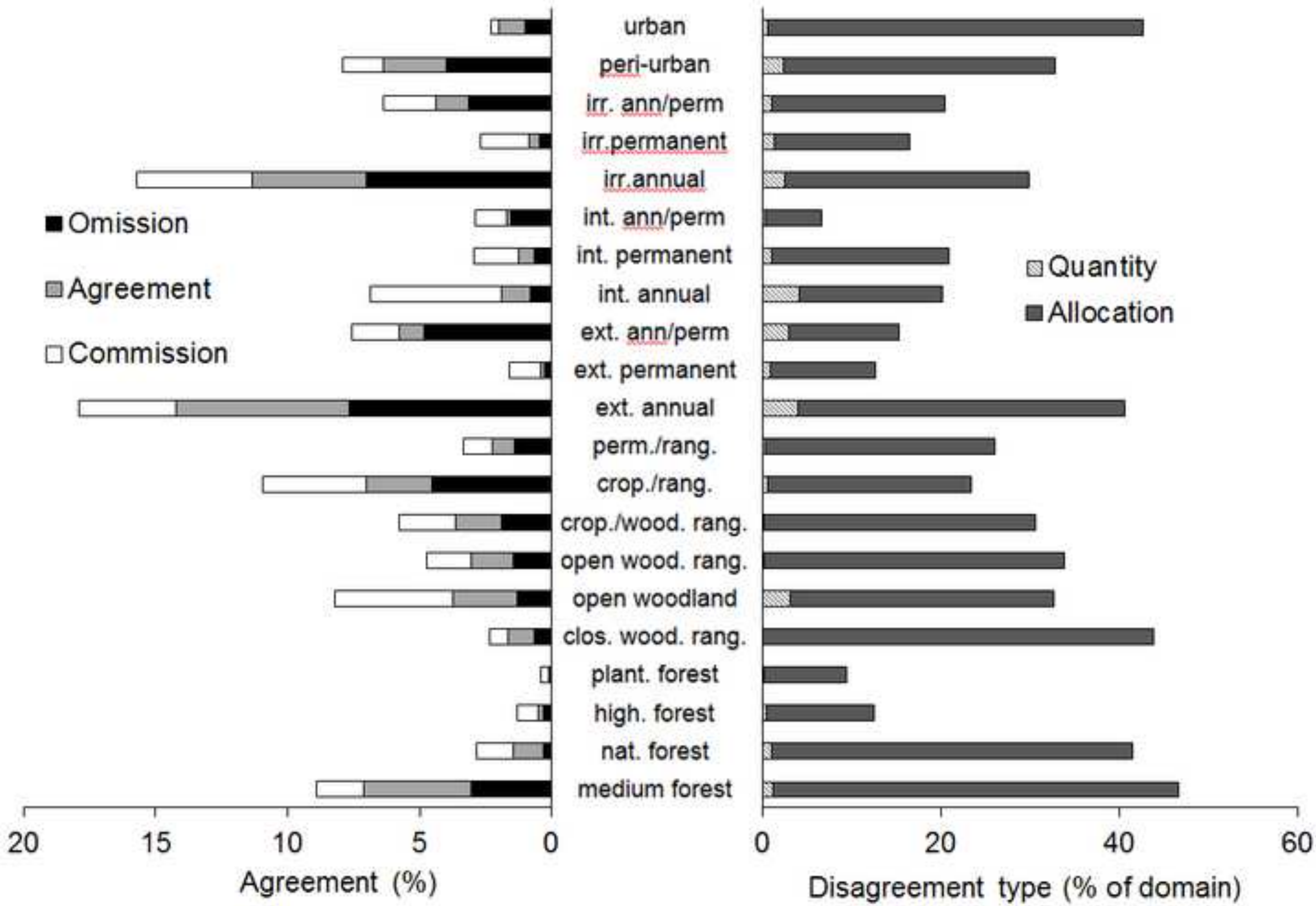
a
b
c
d
e
f
bare / desert
open rangeland
extensive arid grazing
intensive open rangeland
intensive arid grazing
wetlands
cropland and rangeland
open woodland
open wooded rangeland
cropland and wooded rangeland
permanent crops and rangeland
closed wooded rangeland
extensive annual crops
extensive permanent crops
extensive ann-perm mosaic
rainfed intensive annual crops
rainfed intensive permanent crops
rainfed intensive ann-perm mosaic
irrigated annual crops
irrigated permanent crops
irrigated ann-perm mosaic
medium intensity forest
natural and semi-natural forest
high-intensity forest
planted forests
peri-urban
urban


a
0 50 100 200 300
km
b
0 25 50 100 150
km
c
0 50 100 200 300
km
d
0 50 100 200 300
km
e
0 100 200 400
km
f
0 50 100 200 300
km
bare / desert
open rangeland
extensive arid grazing
intensive open rangeland
intensive arid grazing
wetlands
cropland and rangeland
open woodland
open wooded rangeland
cropland and wooded rangeland
permanent crops and rangeland
closed wooded rangeland
extensive annual crops
extensive permanent crops
extensive ann-perm mosaic
rainfed intensive annual crops
rainfed intensive permanent crops
rainfed intensive ann-perm mosaic
irrigated annual crops
irrigated permanent crops
irrigated ann-perm mosaic
medium intensity forest
natural and semi-natural forest
high-intensity forest
planted forests
peri-urban
urban


%
bare, desert 1
ext. open rangeland 0.7
ext. arid grazing 10.2
int. open rangeland 1.8
int. arid grazing 8.9
bare and open grazing systems
%
extensive annual 10.4
ext. permanent 1.3
ext. annual-permanent 2.7
rainfed intensive ann. 5.8
rain. int. permanent 2.2
rain. int. ann.-perm. 1.3
irrigated annual 8.7
irr. permanent 2.2
irr. ann.-perm. 3.3
cropland systems
%
medium intensity forest 6.2
semi(natural) 2.6
high intensity 1
planted forests 0.3
forest systems
%
cropland/rangeland 6.5
open woodland 3.2
open wooded ran. 3.5
cropland/wooded ran. 6.8
perm.crops/wooded ran. 1.7
closed wooded ran. 1.6
agro - silvo - pastoral mosaics


bare (%)
cropland (%)
tree (%)
livestock (nr km²)
20 40 60 80
20 40 60
10 30 50
50 150 250 350
forest systems
wetlands
bare and open grazing systems
agro - silvo - pastoral mosaics
cropland systems
urban systems
medium intensity
natural and semi-natural
high-intensity
planted
wetlands
bare, desert
ext. arid grazing
int. arid grazing
ext. open rangeland
int. open rangeland
closed wooded rangeland
open woodland
open wooded rangeland
cropland/wooded rangeland
cropland/rangeland
perm. crops/rangeland
ext. annual crops
ext. permanent crops
ext. annual-perm. mosaic
rainfed int. annual
rainfed int. permanent
rainfed int.annual-perm.
irrigated annual
irrigated permanent
irrigated annual-perm.
peri-urban
urban


N = 190
misclassification
partially correct
correct
Mediterranean ecoregion


urban
peri-urban
irr. ann/perm
irr.permanent
irr.annual
int. ann/perm
int. permanent
int. annual
ext. ann/perm
ext. permanent
ext. annual
perm./rang.
crop./rang.
crop./wood. rang.
open wood. rang.
open woodland
clos. wood. rang.
plant. forest
high. forest
nat. forest
medium forest
Omission
Agreement
Commission
Quantity
Allocation
20
15
10
5
0
Agreement (%)
0
20
40
60
Disagreement type (% of domain)

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